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The Mid-Infrared Spectrometer on the Infrared Telescope in Space

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ABSTRACT

The Mid-Infrared Spectrometer (MIRS) is one of four instruments that will fly aboard the orbiting Infrared Telescope in Space (IRTS). This telescope is a joint NASA/Japanese Space Agency (ISAS) project that is scheduled for a Spring, 1995, launch aboard a Japanese expendable launch vehicle and subsequent retrieval by the space shuttle. The telescope itself is liquid helium-cooled with a 15 cm aperture and will survey approximately 10% of the sky before its cryogen runs out and it begins to warm up. The MIRS was developed jointly by NASA, the University of Tokyo, and ISAS and operates over a wavelength range of 4.5 to 11.7 microns with a resolution of 0.23 to 0.36 microns. The MIRS has a conventional entrance aperture, so that spectral studies can be made of extended as well as point-sources. A cold shutter and an internal calibrator allow accurate absolute flux determinations. Calibration and sensitivity tests in the laboratory have shown that the instrument sensitivity will be limited by the fluctuations due to the zodiacal dust emission over the wavelength range of the spectrometer. The large A-omega of the spectrometer, the cryogenic optics, and the survey nature of the telescope will allow very sensitive studies of the spectral characteristics of diffuse extended emission. These observations will help in determining the composition of the galactic dust responsible for the warm component of the infrared cirrus. In secondary observing programs, the MIRS will also take spectra of the zodiacal dust emission as well as measure the infrared spectra of an estimated 9,800 point-source objects.

1. INTRODUCTION

The Infrared Telescope in Space (IRTS) is one of seven experiments on the first Space Flyer Unit (SFU-1), scheduled for launch from Tanegashima Space Center in Japan in early 1995. Four scientific instruments and a near-infrared star sensor used for telescope pointing reconstruction share a common focal plane in the telescope. This paper describes one of the instruments, the Mid-Infrared Spectrometer (MIRS). Descriptions of the other three instruments and the telescope facility can be found elsewhere [1, 2, 3, 4, 5, 6]. A brief review of the telescope and mission parameters is given in Section 2, the MIRS science goals are outlined in Section 3, the MIRS design and description is given in Section 4, and the results of the laboratory calibrations are given in Section 5.

2. THE IRTS MISSION

The IRTS is scheduled to be launched on the first Space Flyer Unit mission (SFU-1) from Tanegashima Space Center in early 1995. After separation from the launch booster, the SFU will be inserted into a nearly circular, 482 km *altitude*, 28.5° *inclination* orbit. After a checkout period lasting approximately one week, the IRTS aperture cover will be ejected and observations will begin from all four focal plane instruments for a period of 20 days. Upon termination of the 20 day IRTS observation period, the IRTS will be turned off and other experiments on the SFU-1 will commence. Present tests of the IRTS flight cryostat indicate that the superfluid helium hold time will be approximately 35 days, more than adequate to last through the observation period. After a period of 6-18 months from launch, the SFU-1 is scheduled to be retrieved by NASA's Space Transportation System for refurbishment and reuse in the future.

The IRTS will orbit the earth with the telescope sweeping across the sky at a rate of 0.067° sec^{-1} in great circles that are defined by the various earth and sun avoidance angle constraints [1]. Each of the great circle scans will be offset from one another by approximately 0.07°, or approximately one-half of the MIRS beam size. This means that the IRTS will survey up to approximately 1.3 steradians or 10% of the sky during the anticipated 20 days of IRTS observations.

The IRTS telescope itself is a Cassegrain design with gold-coated aluminum optics [2]. The primary mirror is 15 cm in diameter and the telescope final focal ratio is F/4. The telescope is surrounded by a 100 liter-capacity liquid helium cryostat, which is pumped through a porous plug by the vacuum of space. Tests indicate that the cryostat will operate at an on-orbit temperature of 1.8 K.

3. THE MID-INFRARED SPECTROMETER SCIENCE GOALS

To date, the IRAS mission has provided the most complete and sensitive infrared all-sky survey, surveying approximately 96% of the sky in four infrared wavelength bands centered at 12, 25, 60, and 100 μm [7]. Although there was a low spectral resolution spectrometer operating from 8 to 23 μm included in the IRAS mission, it was of a slit-less design and as such could only be used for observations of point-source objects [8]. A natural follow-on mission to the IRAS mission would include low-resolution spectroscopic capabilities to explore the mid-infrared spectral range in both extended and point-source objects. This new mission would also be able to take advantage of the advances in infrared technology that have occurred since the IRAS mission.

Within the IRTS, the Mid-Infrared Spectrometer will cover the 4.5 - 11.7 μm range with a spectral resolution of 0.23 to 0.36 μm and a sensitivity limited only by the natural zodiacal background throughout most of its wavelength range. The instrument incorporates a standard entrance aperture and can therefore take spectra of both extended and point-sources. A very large number of different scientific investigations are appropriate for study by the MIRS, but three in particular have been selected for the initial studies.

3.1. Spectral studies of diffuse galactic objects.

One of the primary science goals of the MIRS will be to take low-resolution spectra of extended emission regions within the galaxy. The IRAS mission discovered the presence of extended structures of faint emission regions, which were named infrared cirrus after their appearance [9]. Although most of the infrared radiation emitted by these diffuse clouds is in the far-infrared, the result of the low equilibrium temperatures obtained from the interstellar radiation field, these extended clouds have also been observed to have a high temperature component that is bright in the mid-infrared [10]. The vastly lower infrared background of the cooled IRTS telescope will allow the MIRS to take spectra of objects illuminated solely by the interstellar radiation field, as well as the brighter objects illuminated by nearby stronger sources. The wavelength range and spectral resolution of the MIRS will be sufficient to measure the infrared features located at 5.6, 6.2, 7.7, 8.6, 9.7, and 11.3 μm. It will therefore be possible to study possible compositional variations in the galactic high temperature dust components as a function of the energetics in the objects' environments.

3.2. Studies of the Zodiacal Dust.

Although the IRTS mission sun-avoidance constraints will limit the spatial investigations possible at near-sun angles, the MIRS will still be able to investigate possible composition variations in the different dust bands discovered by IRAS. In addition to other features that may be discovered, the MIRS wavelength coverage will be sufficient to measure the extent and depth of the silicate feature near 10 μm in the Zodiacal dust.

3.3. Spectra of IRAS point-source objects.

The Low Resolution Spectrometer (LRS) in the IRAS mission demonstrated the utility of spectral observations of the brighter IRAS point-sources. The MIRS will expand on these investigations for those IRAS sources within the IRTS scan path. Technological advancements since the IRAS mission enable the MIRS to be a factor of 5 times more sensitive than the LRS in the 7.4 to 11.7 μm region of the spectrum. In addition, the MIRS will also extend the spectral coverage below the LRS 7.4 μm wavelength lower limit down to the MIRS limit of 4.5 μm. Estimating the number of possible point-sources that will be seen by the MIRS is difficult, since the IRAS mission did not cover the entire wavelength range of the MIRS, but based on the number of IRAS 12 μm point-sources, the MIRS should be able to take the spectra of an estimated 9,800 sources at signal-to-noises of greater than 3:1 during the IRTS mission lifetime.

4. MIRS INSTRUMENT DESCRIPTION

The modest scale of the IRTS mission presented all of the focal plane instruments with severe size, weight, power dissipation, and data rate constraints. As the IRTS facility did not provide infrared calibration sources, each instrument had to incorporate its own. To meet the MIRS science goals, a low resolution spectrometer operating from 5 to 11 μm was indicated. In order to meet the power and weight constraints, it was decided that the MIRS would have a fixed grating with a cold instrument entrance aperture shutter as the only moving part. Closing this shutter provides an absolute zero infrared background condition for measuring detector dark currents and also blocks the emission of stray infrared light from the MIRS when the internal calibration source is on. Since all of the IRTS focal plane instruments will be operated simultaneously, it was important that all sources of optical, electrical, thermal, and mechanical interference between the instruments be eliminated. The MIRS optical design that was developed to meet the above constraints is shown in Figure 1. The overall specifications are given in Table 1. Further details of the individual MIRS components are given below.

4.1 Optical components.

The IRTS telescope output is divided among the four focal plane instruments and the near-IR star sensor by a set of pick-off mirrors mounted just in front of the telescope focal plane. The IRTS telescope images the sky off of this mirror onto the 1.4 mm x 1.4 mm (8' x 8' field-of-view) MIRS entrance aperture. A 3.4 μm long-pass filter located immediately behind the entrance aperture is used to eliminate second-order dispersed light from the grating at wavelengths shorter than 6.8 μm. The light emerging through the entrance long-pass filter then travels the length of the MIRS and strikes a concave grating which simultaneously refocuses the light onto the field mirror set and disperses it.

The MIRS grating is of a novel design that incorporates variable line spacings and blaze angles in order to both correct for astigmatism and flatten the focal plane [11]. With this grating design, essentially all of the aberrations can be eliminated at a given wavelength by adjusting the groove spacing parameters. In our application, we need to cover a wide range of wavelengths, so the grating parameters were chosen to give the best compromise performance over the entire wavelength range [12]. As a result, there are some un-corrected aberrations (mostly astigmatism) remaining along the dispersion direction for the wavelengths on each side of the 6 μm aberration minimum, which tends to degrade the spectral resolution slightly. With the MIRS grating there are essentially no aberrations in the spatial dimension, so that the spatial resolution of extended sources is not compromised.

The spectrally dispersed image of the MIRS entrance aperture is focused by this grating onto 32 off-axis parabolic field mirrors, each 1.4 mm x 1.4 mm in size. These field mirrors in turn image the grating onto 0.85 mm diameter pupils located immediately in front of the MIRS infrared detectors. Between the field mirrors and the pupils, 6.1 μm long-pass interference filters are used for removing second-order light in the 24 longest wavelength channels. In order to keep the optical path length the same for all the channels, wide-band anti-reflection coated germanium of the same thickness as the long-pass order-sorting filters is located in front of the 8 shortest wavelength channels. The entire inside of the MIRS is highly baffled and is painted with an infrared-absorbing black paint to minimize stray light.

Table 1

MIRS SPECIFICATIONS

Wavelength range:	4.495 to 11.703 µm
Resolution:	0.23 to 0.36 µm
Size:	Irregular shape - 210 mm x 137 mm x 75 mm overall
Weight:	805 g
Electrical power dissipation:	Cold electronics - 4 mW Warm electronics - 2.9 W
Operating temperature:	1.8 K
Detectors:	32 Si:Bi photoconductors, Aerojet ElectroSystems
Entrance Aperture:	1.4 mm x 1.4 mm (0.14° x 0.14° on sky)
Integrating Amplifiers:	Model JF-4, IR Labs
Cold Multiplexers:	CD4067B, RCA Electronics Corp.
Warm electronics package:	Hamamatsu Photonics K. K.
MIRS data rate:	1,188 bits/sec (standard operating mode) 594 bits/sec (reduced data-rate mode)

4.2 Detectors.

The MIRS uses thirty-two individual Si:Bi photoconductor detectors to detect incoming infrared radiation. Detectors of this construction were chosen because of their relative freedom, when biased appropriately, from long-term time-constant effects in low background environments and their relative immunity to radiation-induced responsivity changes [13].

4.3 Cold electronics

Each of the individual detector outputs inside the MIRS is routed through its own integrating amplifier and then into one of two 16:1 multiplexers. The integrating amplifiers were obtained commercially (Infrared Laboratories, Model JF-4) and include internal heaters to prevent carrier freeze-out in their JFET transistors at liquid helium temperatures. A total heater power of 3.0 mW for all 32 units is sufficient to warm the amplifiers enough to meet the MIRS performance specifications of an output impedance of less than 50 k-ohm and a voltage gain of better than 0.9. The other active cold electronics components, the 16:1 CMOS cold multiplexers, dissipate negligible power at the low switching rates of the MIRS. The input capacitance of the integrating amplifiers is 7.5 pF, which means that the output of the amplifiers is approximately 1.2×10^{11} V sec^{-1} amp^{-1}. In order to reduce the noise bandwidth, 0.1 µF capacitors are used to bypass the signal lines from the integrating amplifier outputs to the 16:1 multiplexers to ground. In conjunction with the integrating amplifiers' output impedance, these capacitors act as low-pass filters with corner frequencies of approximately 30 Hz.

Each of the two cold multiplexers consists of a 16-channel commercial CMOS-type unit (RCA Corp., CD 4067B). In order to keep the multiplexer on-state impedance low throughout the output voltage range of the integrating amplifiers, the multiplexers are biased with ±5 volts and are also addressed with ± 5 V logic.

4.4 Warm electronics

The warm electronics package for the MIRS was constructed by Hamamatsu Photonics K. K. of Japan and is diagrammed schematically in Figure 2. The outputs from the two cold multiplexers inside the MIRS each pass in turn through a low-noise x100 DC amplifier and into an offset amplifier. In general, the outputs of the JF-4 integrating amplifier units will all come to different voltage levels immediately after a reset. For each individual integrating amplifier, a unique voltage source is selected by an offset voltage multiplexer and added into the detector output in the offset amplifier, insuring that all of the detector channels will have the same electrical dynamic range. After exiting from the offset amplifier, the signals pass through a low-pass filter and into a junction multiplexer. The junction multiplexer selects between signals from the outputs from the two low-pass filters, the two temperature sensor outputs, and three voltage references. The output of the junction multiplexer is then finally digitized by a Track/Hold amplifier and 16-bit A/D converter combination. The total noise of the detector/electronics system with the bias voltage applied to the detector, no incident infrared flux, and sampling each detector at a 2 Hz rate, was measured to be 180 electrons read^{-1}, referred to the detector.

The MIRS electronics is controlled by a common IRTS instrument electronics package that is responsible for handling all of the data and commands for each of the four focal plane instruments. The MIRS data reads are interleaved in a complicated way with reads from the other instruments. Each individual MIRS detector is read at 2 Hz, but under certain circumstances the MIRS cold multiplexers will switch *between* detectors in times as short as 2 ms. The IRTS common electronics package is also responsible for providing conditioned DC power for each of the focal plane instruments and translating each instruments' parallel data and command signals into serial format for communication with the main IRTS computer.

During most of the IRTS mission, the integrated signal from each MIRS detector output will be sampled at a rate of 2 Hz, allowing four samples in the time it takes a point-source object to cross the MIRS entrance aperture. For a few of the mission orbits, the SFU-1 spacecraft will not pass over the field-of-view of a Deep Space Network receiving station. In these orbits, the recorded data would overflow the onboard memory if the data rate from the instruments were not reduced. As a result, in the case of these orbits, the IRTS will enter a reduced data-rate operations mode where the MIRS detector outputs are sampled at a rate of 1 Hz.

4.5 Calibration source

In addition to calibrations provided by observing standard astronomical sources while scanning the sky, the MIRS will be calibrated every 15 minutes on-orbit by an internal calibration source. Each of these calibration periods will last one minute, during which all of the focal plane instruments on the IRTS will conduct their internal calibrations. The MIRS calibration source consists of a hot metal wire with a tiny drop of black epoxy acting as a black-body emitter. Tests have shown that the wire/epoxy combination heats up reproducibly to a constant emission level in approximately three seconds. The entire wire and epoxy bead assembly is located in an enclosure with a 12.5 μm diameter aperture hole, which defines a point-source and also limits the amount of far-infrared radiation from the MIRS calibration source that might interfere with the other longer-wavelength IRTS focal plane instruments. The calibration source is located at the same angle relative to the grating as is the entrance aperture, but on the other side of the grating. As a result, the wavelength assignments for each detector are reversed, compared to the wavelength assignments for light from the MIRS entrance aperture. Some of the long-pass order sorting filters are therefore in the wrong positions with this scheme, so that little infrared flux is seen in the 8 longest-wavelength detectors. In spite of these disadvantages, tests have shown that the calibration source will reproducibly illuminate all of the 24 shortest-wavelength detectors so that gain and detector responsivity variations can be monitored.

4.6 Thermometry

Two Si diode thermometers (Lakeshore Cryotronics, Model DT-470) are used to monitor the temperature of the MIRS. One of the thermometers is mounted on the base of the MIRS housing, the second is mounted on the MIRS detector block holding the Si:Bi detectors. Both thermometers are biased in series with a common constant-current source and the output voltages from each thermometer are led out of the MIRS into a pair of X3 amplifiers in the MIRS warm electronics package. The outputs from these amplifiers are then sent on to the junction multiplexer in the warm electronics package, as noted above.

5. LABORATORY CALIBRATIONS

The MIRS was tested and calibrated extensively in the laboratory both at NASA/Ames and ISAS prior to delivery to the spacecraft. For the initial tests and calibration, the instrument was mounted at the focal plane of the IRTS flight telescope and both telescope and instrument were enclosed in a special test cryostat located at the Institute for Space and Astronautical Science (ISAS) that reproduced the expected very low on-orbit infrared background. Using this test cryostat, the MIRS was calibrated in the laboratory for sensitivity, telescope focus, spectral range and resolution, polarization, and detector time-constant effects. After these calibrations were performed, the telescope assembly was installed in the IRTS flight cryostat together with the other focal plane instruments, and tests were conducted ensuring that there was no significant interference between any of the instruments while they were all operational. At this time the hold time of the flight cryostat was also measured to be approximately 35 days in on-orbit conditions.

Spectral tests of the MIRS were made with a calibrated circular variable filter, a series of calibrated narrow band-pass filters, and two polymer plastic filters whose absorption spectrum had been previously been determined at NASA/Ames with a Fourier transform spectrometer. The full wavelength coverage of the MIRS was found to range from 4.495 to 11.703 μm, while the center wavelengths for the detectors ranged from 4.608 to 11.590 μm. The relationship between the detector center wavelength and the detector spatial position was almost exactly linear. The measured instrumental FWHM spectral resolution was found to range from a minimum of 0.23 μm at a wavelength of 6.7 μm to a maximum of 0.36 μm at 10.8 μm.

A similar test set up was used to measure the MIRS instrumental polarization, except that a wire grid polarizer was used in front of the black-body instead of the spectral filters. Significant instrumental polarization was observed in the MIRS, with the angle of polarization lying along the grating dispersion direction. The magnitude of the instrumental polarization was found to increase linearly with wavelength, from a value of nearly zero at the shortest wavelengths up to a value of approximately 30% at 11.6 μm.

Finally, tests were conducted to estimate the magnitude of long time-constant effects in the MIRS detectors. Although some of the MIRS detectors were found to exhibit responsivity changes lasting up to 4 minutes in length, the magnitude of these changes was never greater than 8% in the worst cases. These responsivity changes were also observed to increase in magnitude with increases in the infrared flux received, so the realistic responsivity variations are expected to be less than 3% for all except the few very brightest sources seen by the MIRS while on-orbit.

A large aperture (20 cm diameter) plane black-body was placed directly in front of the test cryostat windows for the MIRS sensitivity tests. Measurements were taken at various black body temperatures ranging from 50° C to 200°C. Measurements were also taken at different MIRS operating temperatures to determine the instrument temperature sensitivity. The instrument signal response was found to decrease by a factor of two when the temperature was reduced from 4.2 K to 2.0K. However, the temperature response curve was fairly flat for temperatures near the expected operating temperature; the instrument responsivity changed by only 0.9% when the temperature was increased from 1.75K to 2.17K

Based on the data from these tests, the MIRS on-orbit surface-brightness sensitivity was estimated and is shown in Figure 3 in a λF_λ plot. In this plot, the estimated MIRS 1-σ sensitivity for one MIRS beam size, assuming that the IRTS great circle scans are offset from one another by one-half of an MIRS beam size, is indicated by the filled black diamonds.

This estimate includes the contributions from both the measured instrumental noise as well as the estimated Zodiacal background noise. The fine line associated with the diamonds is the sensitivity limit arising from fluctuations in the Zodiacal background alone. As can be seen, the MIRS is Zodiacal background-limited in sensitivity at all but the shortest wavelengths. The estimated MIRS sensitivity given above is likely to be affected by systematic errors from a number of sources, including uncertainties in the transmission of the test cryostat optical train, less-than-ideal performance of the black body source, and particularly by the fact that the MIRS grating is only being partially illuminated by the beams from the four test cryostat windows. Making our best estimates of the worst-case magnitudes for these systematic error sources, we find that the MIRS sensitivity line in Figure 3 could possibly be moved up or down by as much as the amount indicated by the barred symbol in the figure. As with the spectral resolution, the true instrumental sensitivity will have to be determined by observations of standard sources while on-orbit.

In order to put the estimated sensitivity of the MIRS into perspective, a number of different astronomical sources are also shown in Figure 3. The flux from the Zodiacal pole is shown as open diamonds. The observed flux from a hypothetical one Jy point-source is shown as open squares, as is the observed flux from a hypothetical 1 MJy-steradian^{-1} extended source, shown as open circles. For comparison, the observed spectrum of the extended reflection nebula NGC 7023 [14] is shown. Finally, the spectrum of NGC 7023 is again displayed, but in this case shifted down in flux in order to match the intensity of a typical galactic infrared cirrus cloud observed by IRAS [10]. If this shifted spectrum can be used as an estimate of what may be expected from a typical cirrus cloud, it can be seen that the MIRS will have enough sensitivity to measure the spectral features at a signal to noise of over 5:1, even with the worst-case estimate of the instrument sensitivity.

As can be seen in Figure 3, the MIRS will have the enough sensitivity to take spectra of the Zodiacal light with very high signal-to-noise. The galactic cirrus is expected to be much fainter, but can still be observed with an estimated signal-to-noise of better than 5:1 by the MIRS. If the "generic" IR emission feature strength ratios [15] are used to extrapolate the strength of the 7.7 μm feature from the measured emission from the 3.3 μm feature [16], it can be seen that the diffuse emission from the 7.7 μm feature should be detected by the MIRS to galactic latitudes greater than $|b| < 10°$.

Finally, the high point-source sensitivity of the MIRS will ensure that most of the IRAS 12 μm point-sources will also be bright enough for MIRS spectral studies. Confusion from more than one point source within the MIRS beam may turn out to be the limiting factor at some wavelengths in the ability of the MIRS to detect faint point sources. For the longest MIRS wavelengths, the IRAS data set gives an estimate of approximately 34 sources per square degree that will be seen by the MIRS at the 1-sigma level in the center of the galactic plane ($|b| < 0.05°$, averaged over all galactic longitudes [17]. As the MIRS beam is only 0.14° x 0.14° in size, the average number of IRAS 12 μm point-sources in the MIRS beam within the plane is 0.67. As a result, point-source confusion is only starting to become a problem at the longer MIRS wavelengths. At the short end of the MIRS wavelength range, the situation is likely to be different. At 4.8 μm the MIRS 1-sigma point-source sensitivity is approximately 0.2 Jy or +7.2 magnitude. Estimating the density of sources at this wavelength is difficult, but an upper limit can be approximated by using the density of 2.2 μm sources from the sky model of Cohen, *et al.* [17]. Using this model in the galactic plane ($l = 49.7°$, $b = 0.16°$) we find a number density of approximately 100 sources per square degree brighter than +7.2 magnitude at K (2.2 μm). For the MIRS beam this translates into an average of 2 sources per beam in the galactic plane. It is therefore likely that the MIRS will be confusion-limited at its shortest wavelengths within the galactic plane.

6. CONCLUSIONS

A Mid-Infrared Spectrometer for the Infrared Telescope in Space mission has been constructed, tested, and calibrated in the laboratory. The MIRS has met all of the design objectives and will be able to make a very high sensitivity survey of up to 10% of the sky, including both point-sources and extended objects. This high sensitivity will allow spectral studies of low surface-brightness extended objects, the Zodiacal dust emission, and many of the point-sources in the IRAS survey.

7. ACKNOWLEDGMENTS

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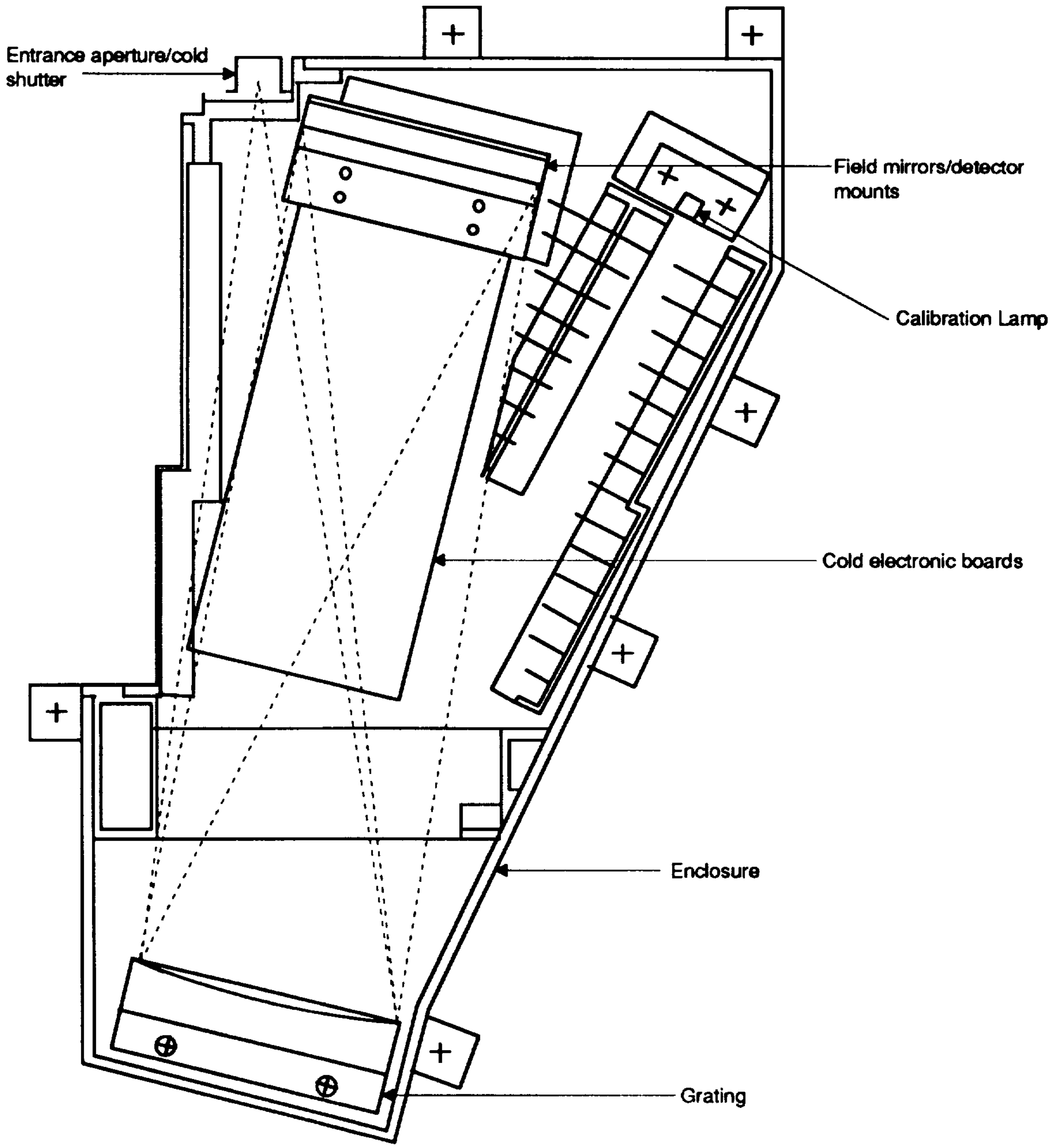

Figure 1. Schematic diagram of the optical layout of the Mid-Infrared Spectrometer.

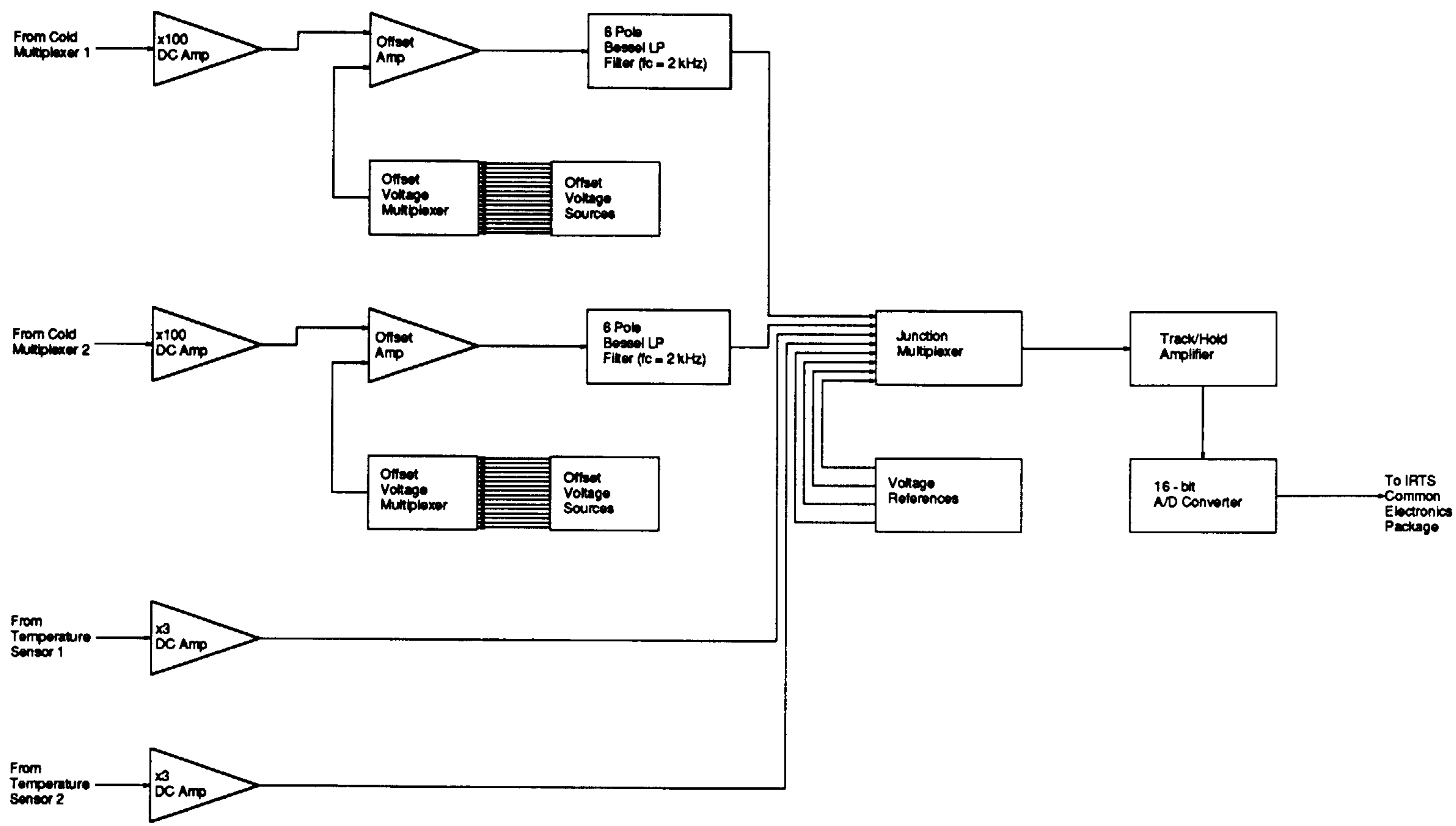

Figure 2. Schematic diagram of the warm electronics for the Mid-Infrared Spectrometer.

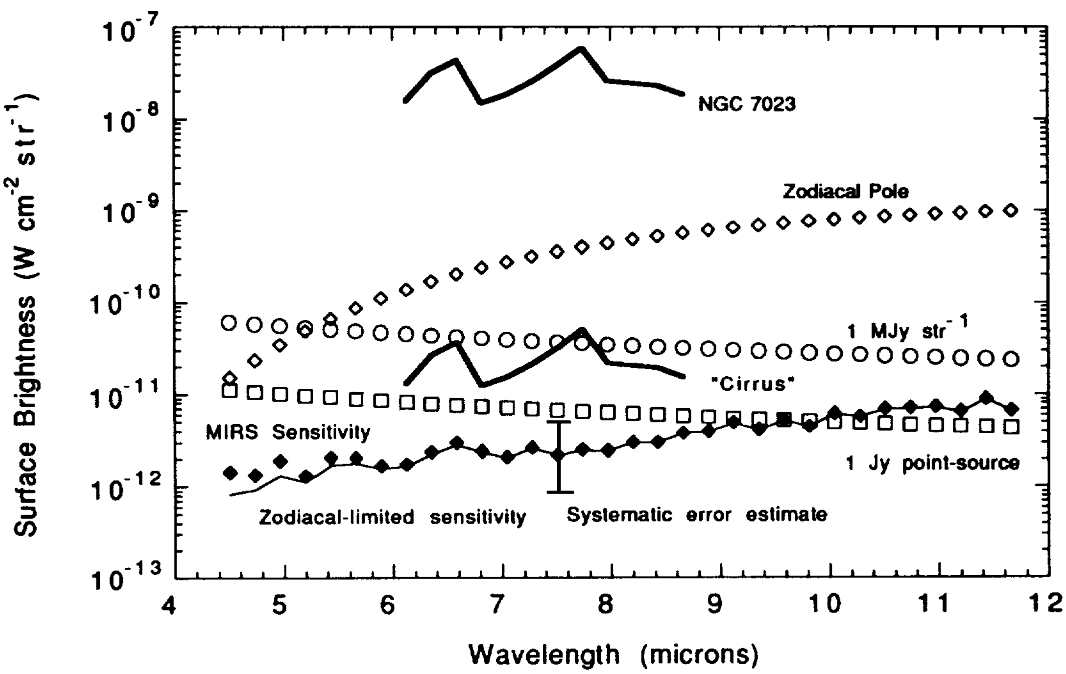

Figure 3. The sensitivity of the MIRS in a λF_λ plot, expressed as a 1-σ surface-brightness limit. The total predicted sensitivity of the MIRS is shown by the filled diamonds. The sensitivity limits imposed by fluctuations in the Zodiacal background are shown by the fine line associated with the filled diamonds. The worst-case estimate of the effects of systematic errors in the laboratory calibration are shown by the barred symbol. For comparison, the surface-brightness of various infrared sources is also indicated and are explained in more detail in the text.